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TECHNICAL REPORT ARCCB-TR-88038

**RESIDUAL STRESS IN  
QUENCHED STEEL CYLINDERS**

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**OCTOBER 1988**

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1. REPORT NUMBER ARCCB-TR-88038	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) RESIDUAL STRESS IN QUENCHED STEEL CYLINDERS		5. TYPE OF REPORT & PERIOD COVERED Final
7. AUTHOR(s) M. E. Todaro, M. A. Doxbeck, and G. P. Capsimalis		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army ARDEC Benet Laboratories, SMCAR-CCB-TL Watervliet, NY 12189-4050		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS US Army ARDEC Close Combat Armaments Center Picatinny Arsenal, NJ 07806-5000		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 6111.02.H610.0 PRON No. 1A7AZ703NMSC
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE October 1988
		13. NUMBER OF PAGES 15
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Presented at ASM Conference on Residual Stress - In Design, Process and Material Selection, Cincinnati, OH, 27-29 April 1987. Published in Proceedings of the Conference.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Residual Stress, Steel Stress, X-Ray Diffraction, Heat Treatment, Ultrasonics, Quenching, Quench Cracking. (finger) ←		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Measurements were made on high strength, low allow steel cylinders to determine the residual stress distributions resulting from various heat treatments. Cylinders of 239-mm outer diameter and 94-mm inner diameter were austenitized at 843°C and quenched at various rates to 93°C. Residual stress measurements were made on cylindrical cross sections which had been cut from the larger cylinder at least one foot from the nearest end. Using ultrasonic and x-ray diffraction techniques, we measured tangential and radial components of stress as a function of radial position.		

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## INTRODUCTION

In the heat treatment of steel, a fast quench rate is often necessary to produce the desired martensitic phase but can result in cracking and undesirable stress states. This report presents various measurements of residual stress distributions in quenched steel cylinders. The stress measurements were made with plane shear ultrasonic waves using the acoustoelastic effect and with X-ray diffraction using single-exposure and multiple-exposure techniques.

## SPECIMEN PREPARATION

Residual stress measurements were made on cylindrical specimens cut from a long hollow cylinder of ASTM A723 steel (MIL-S-46119A) with an outer diameter of 239 mm and an inner diameter of 94 mm. Two different heat treatments were chosen. In the first treatment, the entire cylinder was austenitized at 843°C and quenched to 93°C in 12 minutes using an outer-diameter quench. A 3-inch thick cylindrical section was cut from near one end, 1 foot from the end itself, taking care not to heat the specimen to the point where stresses might be relieved by annealing. Both faces of the section were then wet-ground, leaving them parallel and 2 inches apart. The same large cylinder was again austenitized at 843°C, but then quenched to 93°C in 25 minutes using an outer-diameter quench. A 2-inch thick section was taken from one end, 1 foot from the end, as before. The faces were then wet-ground, leaving them parallel and 1.11 inches apart. The ultrasonic data was taken after each specimen was prepared in this way.

After taking the ultrasonic data, we prepared each specimen for X-ray diffraction by electropolishing a portion of its face, removing a 0.1-mm thick layer of surface material that might contain residual stress due to machining and grinding.

## ULTRASONIC TECHNIQUE

### Theory

The change in velocity of an acoustic wave in a solid due to stress is known as the acoustoelastic effect. If the relation between stress and velocity is known, measurement of the velocity of an acoustic wave can, at least in principle, be used to determine the stress.

Hughes and Kelly (ref 1), Bach and Askegaard (ref 2), and Husson and Kino (ref 3) have derived expressions for the velocities of acoustic waves in homogeneously stressed solids. The velocity,  $V$ , of a plane shear wave propagated along the 1-axis and polarized along the 2-axis is given by the following expression, adapted from these authors:

$$\rho V^2 = \mu + \frac{1}{3\lambda + 2\mu} [(3\lambda + 2\mu)\sigma_1 + (3\lambda + 2\mu + \frac{3n\lambda}{4\mu} + \frac{n}{2})(\sigma_1 + \sigma_2) + (m - \frac{n}{2} - 2\lambda - \frac{n\lambda}{2\mu})(\sigma_1 + \sigma_2 + \sigma_3)] \quad (1)$$

Here,  $\lambda$  and  $\mu$  are the Lamé constants (second-order elastic constants), while  $m$  and  $n$  are two of the three Murnaghan constants (third-order elastic constants).  $\rho_0$  is the density of the undeformed medium. The  $\sigma$ 's are the triaxial principal stresses along the 1-, 2-, and 3-axes.

For the type of steel encountered in our research, the factor  $(m - n/2 - 2\lambda - n\lambda/2\mu)$  is essentially zero as shown by Frankel et al. (ref 4). For situations where  $\sigma_1$  is negligible as well, Eq. (1) can be further simplified to

<sup>1</sup>D. S. Hughes and J. L. Kelly, "Second-Order Elastic Deformation of Solids," Phys. Rev., Vol. 92, 1953, p. 1145.

<sup>2</sup>F. Bach and V. Askegaard, "General Stress-Velocity Expressions in Acoustoelasticity," Exp. Mech., Vol. 19, 1979, p. 69.

<sup>3</sup>D. Husson and K. S. Kino, "A Perturbation Theory for Acoustoelastic Effects," J. Appl. Phys., Vol. 53, No. 11, Pt. 1, 1982, p. 7250.

<sup>4</sup>J. Frankel, W. Scholz, G. Capsimalis, and W. Korman, "Residual Stress Measurement in Circular Steel Cylinders," Proceedings of Ultrasonics Symposium, Vol. 2, 1983, p. 1009.

$$\frac{\Delta V}{V_0} = \frac{1}{2\mu(3\lambda+2\mu)} (3\lambda + 2\mu + \frac{3n\lambda}{4\mu} + \frac{n}{2})\sigma_2 \quad (2)$$

where  $\Delta V/V_0$  is the relative change in velocity due to the stress.

Although these solutions are derived for homogeneous stress, they may also be used for an inhomogeneous stress that does not vary greatly over a distance of one wavelength.

### Experimental Details

We measured shear wave velocities with a pulse-echo technique using a computer-controlled phase-detection system (Matec Instruments, Model MBS-8000), shown schematically in Figure 1. The system uses phase-detection methods that involve interactive computer control of the frequency and measurement of phase relationships. As indicated by the figure, the transducer converts an electrical pulse into a shear wave that travels through the specimen. Each time an echo strikes the front face, it is converted into an electrical pulse that is then amplified and sent to a pair of phase detectors. From the phase detectors, the computer receives signals proportional to the sine and cosine of the echo pulse's phase with respect to a reference wave. The computer can then calculate the amplitude and phase of the echo pulse. Because the phase can only be calculated as an angle between  $-\pi$  and  $+\pi$ , the system varies the frequency slightly and measures the corresponding phase shifts for one or more echoes. From this phase data we may calculate the transit time of the shear wave through the specimen and deduce its velocity.

The measurement of stress, however, requires an accuracy that can only be achieved by measuring changes in transit time as the system is perturbed. For mapping stress distributions, that perturbation is the relocation of the transducer on the specimen's face. By measuring the phase shift due to a change in transducer position, the computer can calculate the corresponding time change.

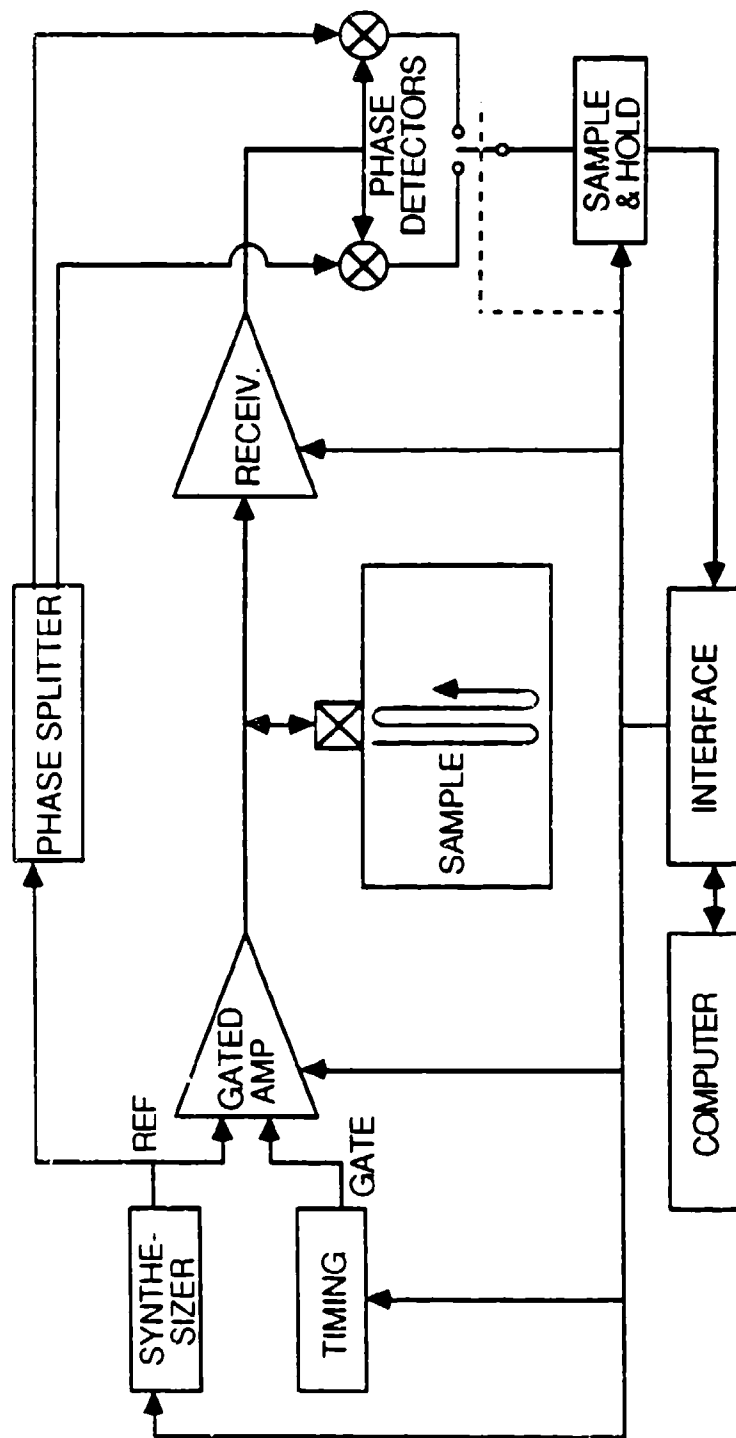


Figure 1. Schematic diagram of computer-controlled phase-detection system to measure ultrasonic velocities.



The system was used with a pulse frequency of 5 MHz and duration of several microseconds. A normal incidence shear wave transducer (Panametrics, V156) introduced shear waves into the specimen and received echoes. The transducer was acoustically coupled to the specimen with a viscous resin (KB-Aerotech, SLC-70) and held in place by hand. Velocity variations were mapped at 0.1-inch intervals along four radial directions as shown in Figure 2. To calculate the tangential (hoop) component of stress through Eq. (2), we polarized the shear wave tangentially. To calculate the radial component, we polarized the wave radially.

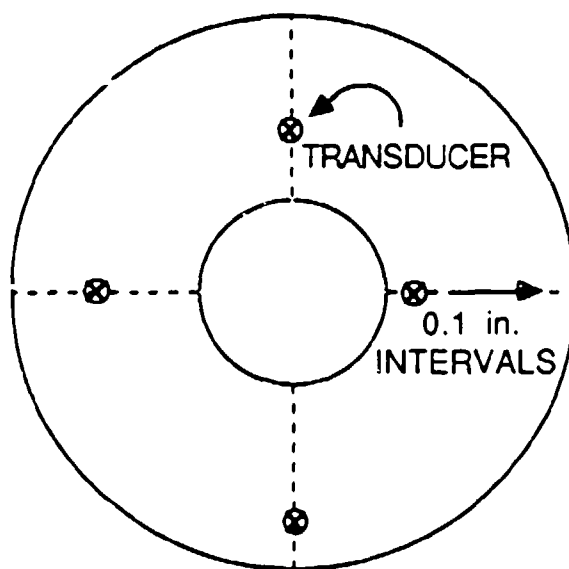


Figure 2. Transducer positions on face of specimen.

## X-RAY DIFFRACTION TECHNIQUES

### Theory

In the single-exposure technique, two diffraction patterns are obtained simultaneously in a single X-ray exposure, as drawn in Figure 3. The incident X-ray beam strikes the specimen at an angle  $\beta$  with the surface normal and is diffracted by atoms in the lattice. In the plane of the incident beam and the

surface normal, two diffraction peaks are observed at angles  $\alpha_1$  and  $\alpha_2$  with respect to the incident beam. The component of stress parallel to the surface and in the plane of the incident beam and the surface normal can then be related to the positions of the diffraction peaks with the expression (refs 5,6)

$$\sigma = \left(\frac{E}{1+\nu}\right) \frac{\alpha_2 - \alpha_1}{4 \sin^2 \theta_0 \sin(2\beta)} \quad (3)$$

In this equation,  $\theta_0$  is the Bragg diffraction angle for the unstrained material,  $E$  is Young's modulus, and  $\nu$  is Poisson's ratio.

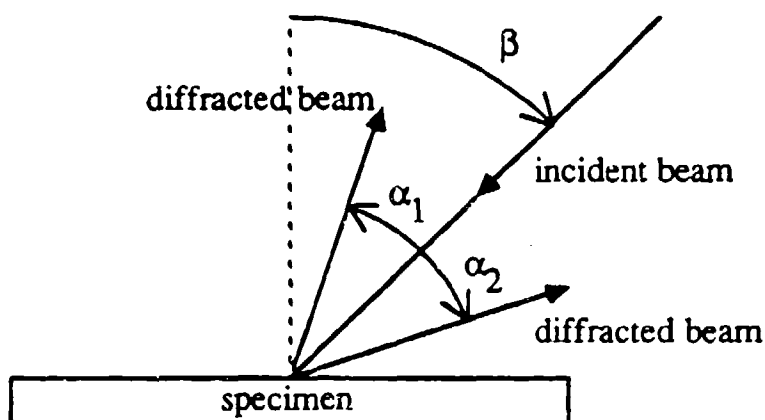


Figure 3. Single-exposure X-ray diffraction technique.

The multiple-exposure technique (refs 5,7), also known as the  $\sin^2 \psi$  technique, relies on the relation

$$\frac{d_\psi - d_0}{d_0} = \left(\frac{1+\nu}{E}\right) \sigma \sin^2 \psi \quad (4)$$

<sup>5</sup>H. P. Klug and L. E. Alexander, X-Ray Diffraction Procedures for Polycrystalline and Amorphous Materials, Second Edition, John Wiley and Sons, New York, 1974.

<sup>6</sup>J. T. Norton, "X-Ray Stress Measurement by the Single-Exposure Technique," Advances in X-Ray Analysis, Vol. 11, 1968, p. 401.

<sup>7</sup>"Residual Stress Measurement by X-Ray Diffraction," SAE J784a, Society of Automotive Engineers, Inc., Warrendale, PA, 1971.

where  $d_\psi$  is the distance between diffracting planes whose normal makes an angle  $\psi$  to the surface normal;  $d_0$  is the distance between diffracting planes parallel to the surface. The term  $(d_\psi - d_0)/d_0$  is plotted for several values of  $\psi$ , and  $\sigma$  is obtained from the slope of the resulting line.

### Experimental Details

Diffraction peaks for the single-exposure technique were obtained and analyzed with a Denver X-ray Instruments Model D-1000-A system. The system uses a miniature X-ray tube and collects diffraction peak profiles using two Ruud-Barrett position-sensitive scintillation detectors (refs 8,9). Each detector consists of a fiber optic bundle with its end covered by a cadmium-zinc-sulfide scintillation coating. The coating converts the diffracted X-rays to light pulses that then travel along the fibers, are amplified by an image intensifier, and directed to a 512 photodiode array. Each photodiode charges a capacitor to a level proportional to the amount of incident light.

The X-ray tube used a chromium target and a beryllium window, providing chromium  $K\alpha_1$  radiation, with a wavelength of 2.29 Å. The system was used with  $\beta$  at 20 degrees and with the two detectors centered on the 211 peak of iron ( $\theta_0$  approximately equal to 78 degrees).

Data for the multiple-exposure technique was taken using a computer-controlled system based on a Siemens stress goniometer (ref 10), which also used chromium  $K\alpha_1$  radiation and scanned the 211 peak of iron.

<sup>8</sup>C. O. Ruud, "Position-Sensitive Detector Improves X-Ray Powder Diffraction," Ind. Res. Dev., Vol. 25, No. 1, January 1983, p. 84.

<sup>9</sup>C. O. Ruud, P. S. DiMascio, and D. J. Snoha, "Miniature Instrument for Residual Stress Measurement," Advances in X-Ray Analysis, Vol. 27, Plenum Press, NY, 1984, p. 273.

<sup>10</sup>G. P. Capsimalis, R. F. Haggerty, and K. Loomis, "Computer Controlled X-Ray Stress Analysis for Inspection of Manufactured Components," Technical Report WVT-TR-77001, Watervliet Arsenal, Watervliet, NY, January 1977.

## RESULTS AND DISCUSSION

The change in shear wave velocity data was converted to stress using a simplified form of Eq. (2),

$$\sigma = A \frac{\Delta V}{V_0} \quad (5)$$

where  $\sigma$  refers to the stress component in the direction of polarization. For the type of steel used in this study, it has been found that  $A = -2630$  MPa (ref 4). Figures 4 and 5 show the results for the 12-minute quench and 25-minute quench specimens. Both cases show a compressive tangential stress at the outer diameter. The tangential stress becomes tensile with increasing depth. In the fast quench specimen, it again becomes compressive toward the inner diameter.

The preliminary results of the X-ray diffraction analysis show qualitative agreement with the ultrasonic results. Figures 6 and 7 show the tangential stress distributions for the 12-minute quench as obtained with the single-exposure and multiple-exposure techniques. Despite a high level of scatter in the data, one can observe that the stress is compressive at the outer diameter, changes to tensile with increasing depth, and again becomes compressive toward the inner diameter. The large scatter in the data is likely due to the broadness of the diffraction peaks, a direct result of the high quench rate. Furthermore, we might expect the X-ray data to differ somewhat from the ultrasonic data because the X-rays only penetrate the specimen to a depth of about 10  $\mu\text{m}$ . The ultrasonic technique uses a wave that travels through the thickness of the specimen, averaging out velocity variations along the wave's path.

One problem with the radial stress distribution for the slow quench tube, Figure 5, is that it shows a high compressive stress at the outer diameter, an

<sup>4</sup>J. Frankel, W. Scholz, G. Capsimalis, and W. Korman, "Residual Stress Measurement in Circular Steel Cylinders," Proceedings of Ultrasonics Symposium, Vol. 2, 1983, p. 1009.

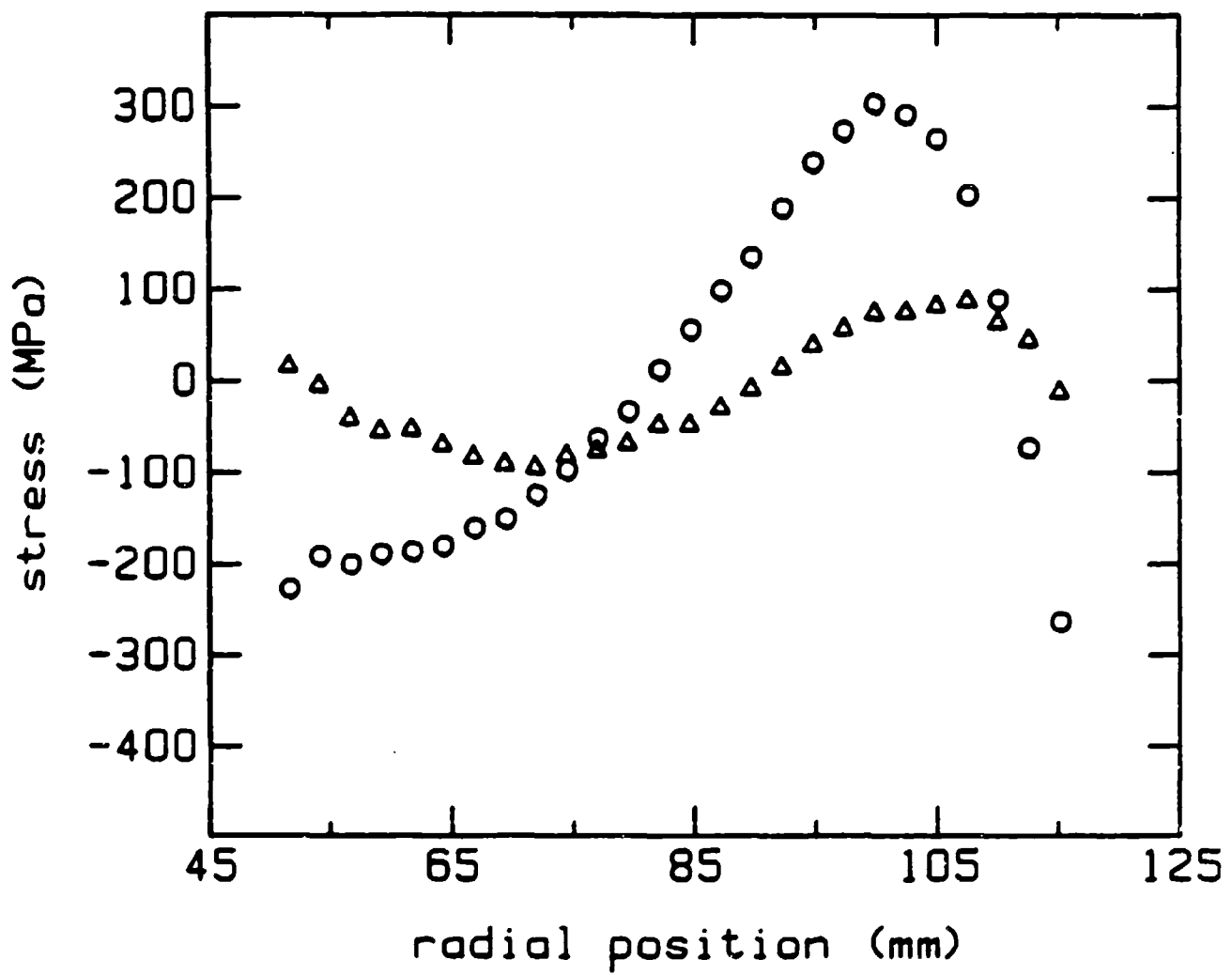


Figure 4. Tangential (circles) and radial (triangles) stress for 12-minute quench specimen using ultrasonic technique.

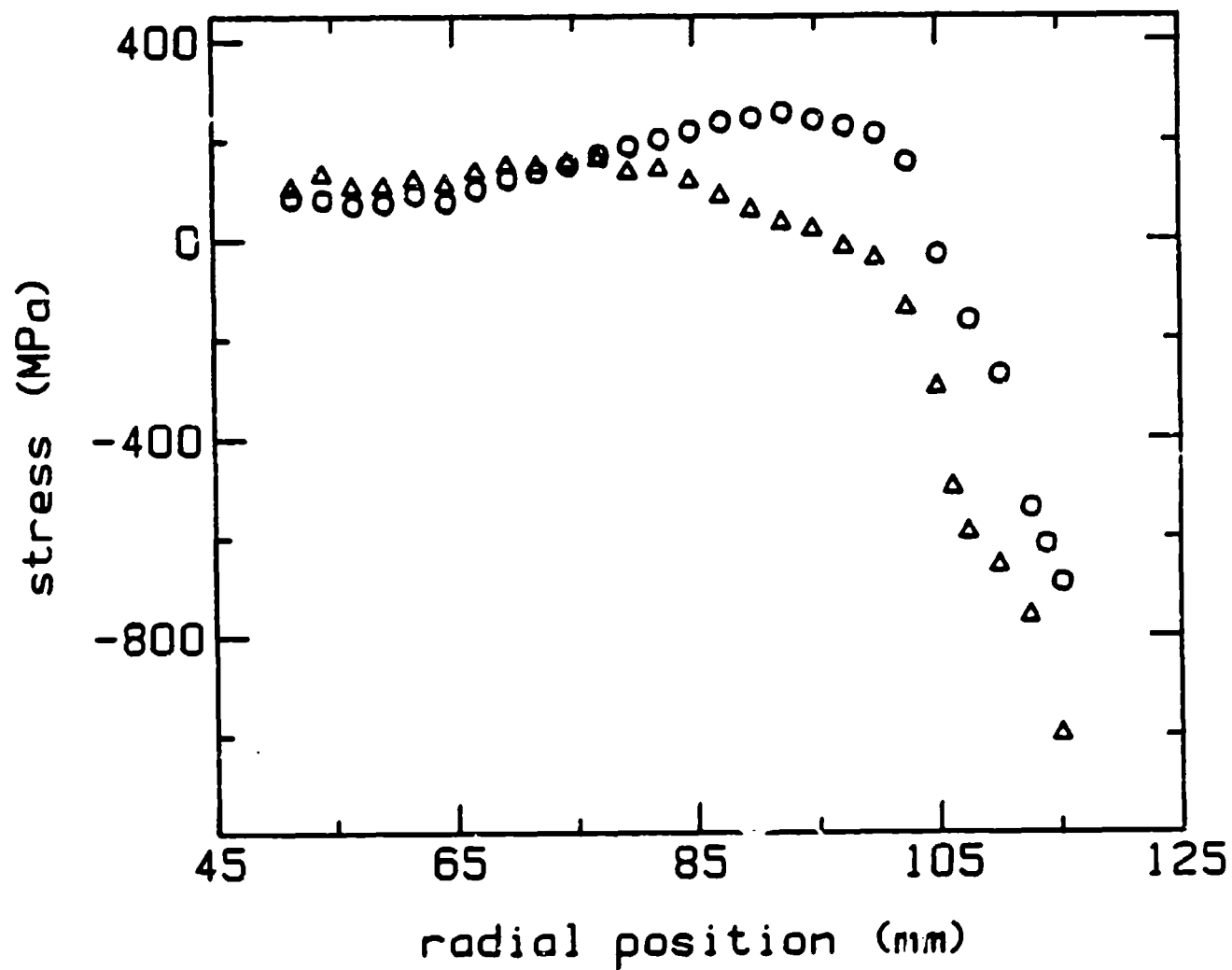


Figure 5. Tangential (circles) and radial (triangles) stress for 25-minute quench specimen using ultrasonic technique.

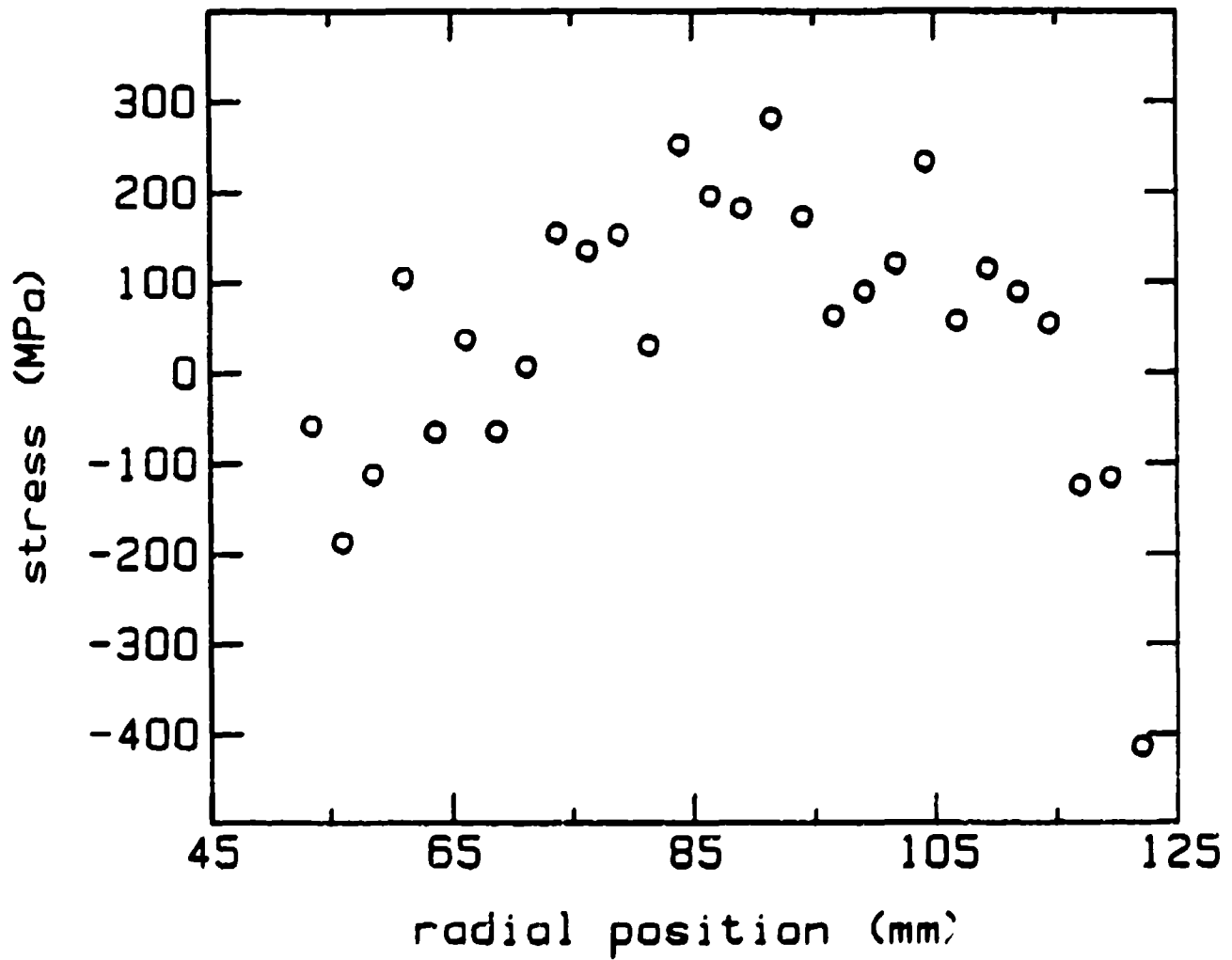


Figure 6. Tangential stress for 12-minute quench specimen using single-exposure X-ray diffraction technique.

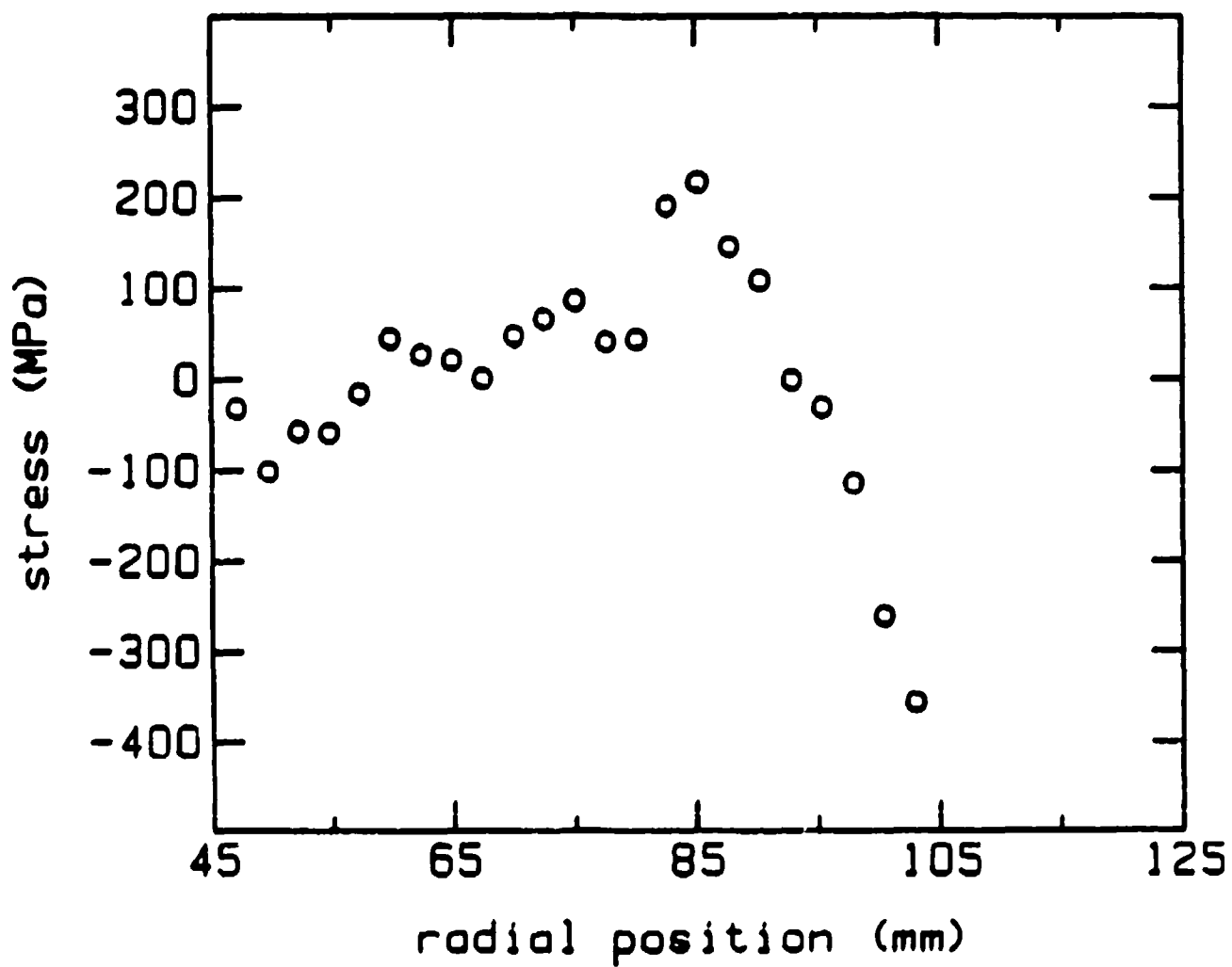


Figure 7. Tangential stress for 12-minute quench specimen using multiple-exposure X-ray diffraction technique.



obvious impossibility. A possible explanation is that we are not really sampling the stress at the actual surface because of the finite width of the transducer.

One of the major problems with use of the ultrasonic technique to measure residual stress is that a preferential alignment of grains results in an elastic anisotropy that can cause velocity variations at least as large as those due to applied or residual stress (ref 11). Although the ultrasonic technique is relatively fast and easy to use, the possibility of velocity changes due to preferred grain orientation reduces our confidence in the results.

Future work will concentrate on verifying the remainder of the ultrasonic data using X-ray diffraction and on calculating theoretical stress distributions based on available models of the quench process.

<sup>11</sup>D. I. Crecraft, "Ultrasonic Measurement of Stresses," Ultrasonics, Vol. 6, No. 2, April 1968, p. 117.

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10. G. P. Capsimalis, R. F. Haggerty, and K. Loomis, "Computer Controlled X-Ray Stress Analysis for Inspection of Manufactured Components," Technical Report WVT-TR-77001, Watervliet Arsenal, Watervliet, NY, January 1977.
11. D. I. Crecraft, "Ultrasonic Measurement of Stresses," Ultrasonics, Vol. 6, No. 2, April 1968, p. 117.

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